Chapter 1

Introduction

1.1 Towards all-optical networks

The existing transport infrastructures are based on technologies foreseen during the '90s when the focus was on providing a guaranteed level of performance and reliability for voice calls and leased lines. But the trend in networking of the last decade reveals that the Internet and IP[1] are becoming the dominant solution, reaching world-wide diffusion and acceptance. Born as a research and university network, providing basic services like e-mail and file transfer, Internet has been growing at an exponential rate. The last network generation consequently deployed solutions capable of fulfilling the capacity requirements of present and future data traffic in both wide and metro environments. The optical technology and in particular the Wavelength Division Multiplexing (WDM) systems are been deeply introduced to increase the bandwidth-carrying capacity of a single optical fiber by effectively creating multiple virtual fibers, each carrying multigigabits of traffic per second, on a single fiber. This network evolution leads to today's network infrastructure which typically comprise four layers: IP for carrying applications and services, ATM for an efficient path management of the network, SONET/SDH for a robust transportation, and WDM for a wide capacity.

The economical crisis during 2001 has shown the drawbacks of current four-layer Internet infrastructure which limit its scalability in terms of dimension, services and business. Indeed multilayer architectures suffer from the lowest common denominator effect where any one layer can limit the entire network, as well as add to the cost of the entire network. As a result the existing transport infrastructure has been currently overcome by a new network model based on IP over WDM (i.e., IP traffic transported directly over optical networks) [52] [78]. This means that the intermediate layer functionalities (essential for a proper network behavior) must move to the other layers. In the end, this results in a simpler, more cost-efficient network that will transport wide range of data streams and very large volume of traffic.

On the other hand, the purely connectionless and *best effort* IP paradigm seems however insufficient to fulfil the needs of new multimedia and interactive applications. Works are ongoing to evolve Internet by optimizing the network efficiency with the

[1]see Appendix A for the list of acronyms

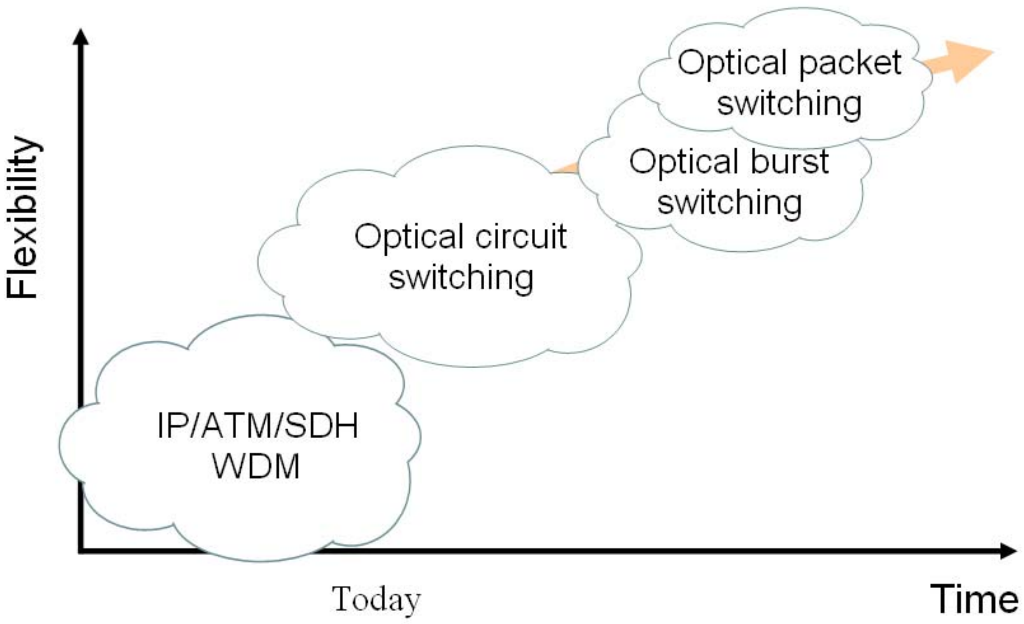

Figure 1.1: Trend of the optical networking technology

integration of Traffic Engineering (TE) [92] functionalities and providing effective Quality of Service (QoS) [89] capabilities. In this direction, proposals such as the Multi-Protocol Label Switching (MPLS) standard [91] and the Differentiated Services [90] architecture can provide the tools for effective QoS management and TE in the Internet.

Definitely, developing optical networks with QoS and TE capabilities is the main goal for next generation telecommunication networks. In this perspective an intense debate has been ongoing about which is the optical network model to adopt, aiming at identifying the degree of optical transparency to be achieved, and the proper flexibility of optical interconnections. Figure 1.1 foresees such trend showing the possible steps from today point-to-point transmission towards more flexible network implementations. We can recognize the current network architecture in the first bubble on the bottom-left side of the Figure 1.1 (i.e., IP/ATM/SDH/WDM).

The first step in the future is the introduction of some flexible mechanisms in WDM networks. The GMPLS technology provides an intelligent control plane (signaling and routing) functionalities for devices that switch in any of these domains: packet, time, wavelength, and fiber with minimum human interaction. This common control plane promises to simplify network operation and increase the network utilization. The basic challenge for an all-encompassing control protocol is the establishment, maintenance, and management of traffic-engineered paths to allow the data plane to efficiently transport user data from the source to the destination [3] [4] [44]. As shown in Figure 1.2, the traffic-engineered paths are physical circuits called *lightpaths* established between two end-points. The network nodes, called *optical cross-connects* (OXCs), are basically space switches which connect input and output ports on a per-wavelength basis, with or without wavelength conversion. When a

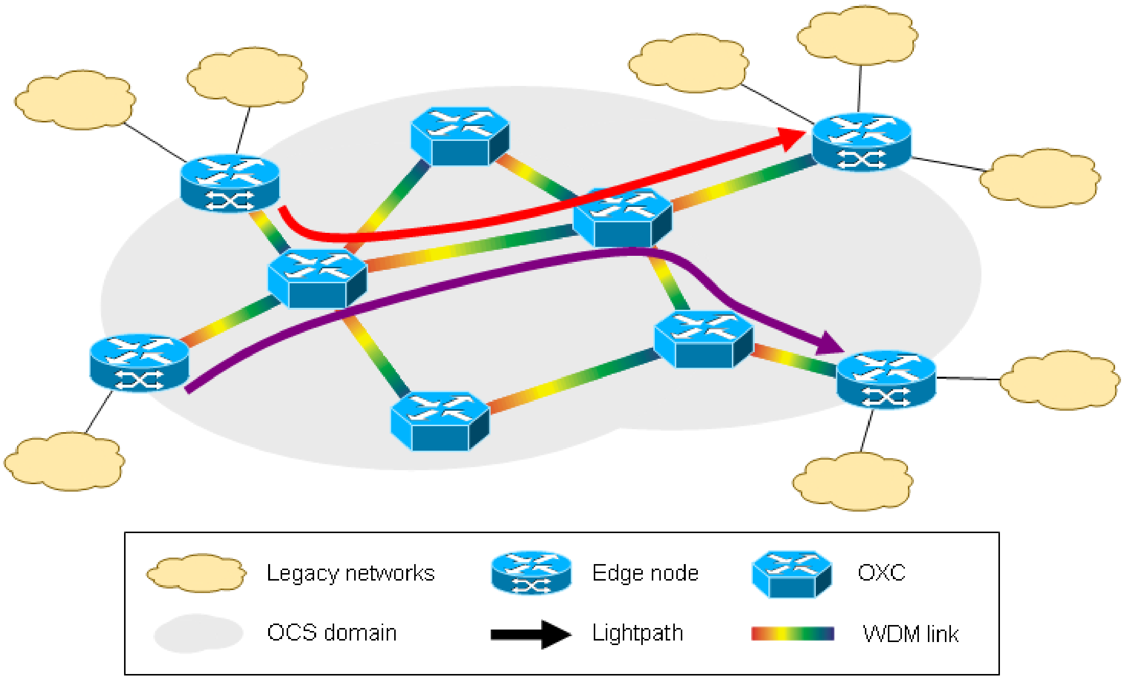

Figure 1.2: Optical circuit switching solution

node requires to establish a new lightpath for a given traffic flow, it sends a signalling request along a route. If the request can be completely accommodated, each OXC reserves the resources configuring its switch matrix. Resulting optical circuit switched (OCS) networks can offer explicit transfer guarantees and some degree of flexibility.

Toward full network utilization, the OCS networks present some drawbacks. They need considerable delay to confirm circuit establishment due to the both propagation delay and optical cross-connects reconfiguration. The network consists of a complex, heterogeneous structure with no easy manageability for protection/restoration, TE, and scalability/upgradability issues. These problems redirect the research community toward solutions able to offer high utilization, probably cope with high traffic churn and a significant portion of bursty traffic [38], deliver connection-oriented services and need to be cost effective too. Handling finer granularity connections appears therefore the aim of next generation networks where packet-based networks, such as Internet, will play a predominant role.

At this point, it is important to consider the emerging all-optical devices. In spite of the extraordinary advances in transmission capacity, optics has not penetrated much into the switching and management part of the network and all-optical networks are still in their infancy. New optical components such as Tunable Wavelength Converters (TWCs), Semiconductor Optical Amplifiers (SOAs), 3R optical regenerators are currently under development aiming at providing very high integration degree and very low power consumption [87] [33].

These new devices open up new possibilities where a finer granularity with respect to the OCS solution can be realized with the Optical Burst Switching (OBS) and

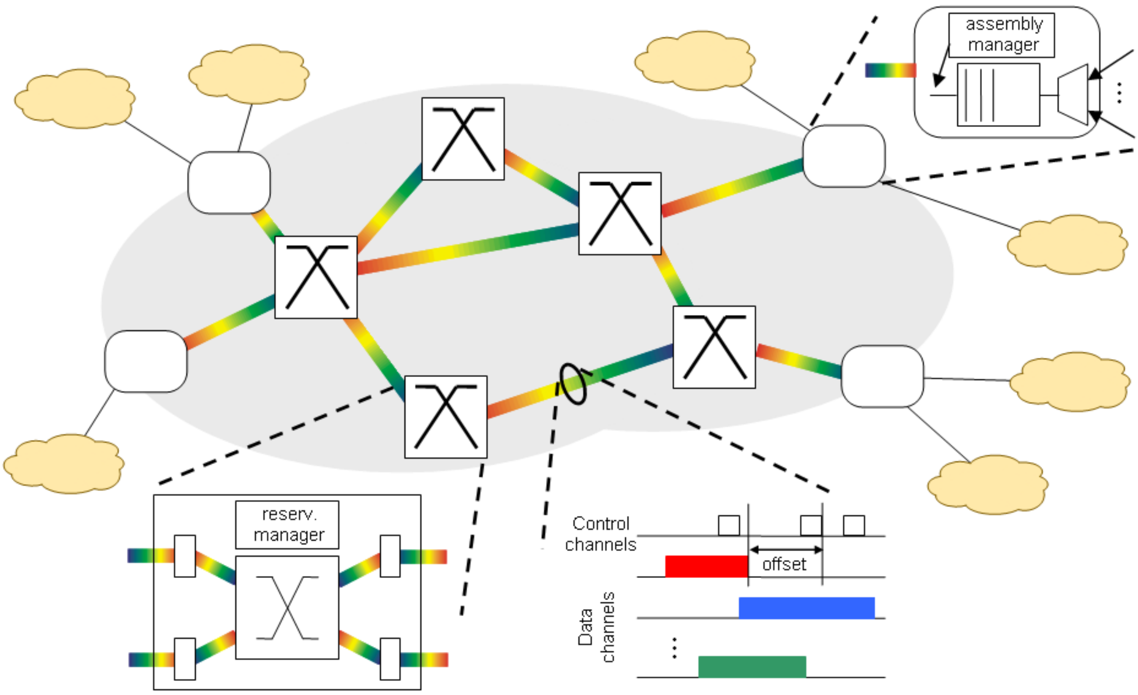

Figure 1.3: Optical burst switching solution

Optical Packet Switching techniques. Both switching technologies do not require a two-way end-to-end signalling, as data is optically transferred across the network without waiting to set-up the entire path. Instead of over-provisioning of circuits, these solutions apply the packet switching techniques directly in the optical transport network bringing more statistical sharing of the physical resources to reduce the connection costs.

OBS networks [86] (see Figure. 1.3) are characterized by a separation of data and control channels. At first, a control packet is sent to support intermediate nodes configuration and resource reservation; meanwhile the source node builds the corresponding burst aggregating incoming packets with the same characteristics (destination, QoS level, etc.); when ready, the burst is sent and optically switched across the network. This means that only control packets are electro-optical converted at each hop to take reservation decisions, while the bursts always remain in the optical domain.

OPS networks [62] (see Figure 1.4) use finest switching granularity and require very fast all-optical switches (switching time in the order of nanoseconds). Control and data information travels together in the same channel; each intermediate node converts the control headers to take switching decisions while the packets always remain in the optical domain.

Both solutions improve wavelength utilization by introducing statistical multiplexing directly in the optical domain. This cause that data contentions may arise at the nodes and therefore contention resolution policies must be applied to reduce the losses probability and make the statistical sharing more efficient. In electrical so-

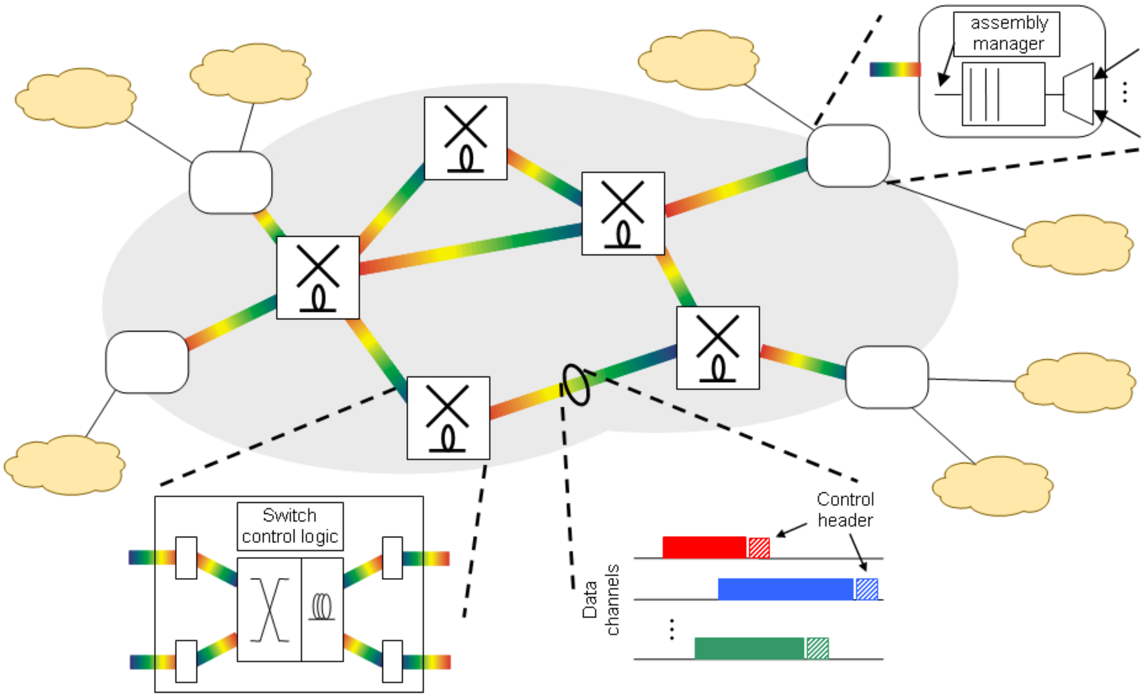

Figure 1.4: Optical packet switching solution

lutions, contention resolution may usually performed in the space domain, by means of deflection routing, and in the time domain, by means of queuing. In optics, the lack of optical RAMs imposes the use of a pool of Fiber Delay Lines (FDLs) [48] which are bulky and not scalable and offer limited buffering capabilities (few tens of delays at maximum [45]). Nonetheless, optics can exploit the WDM links and wavelength converters and therefore solve contention also in frequency domain, by means of wavelength multiplexing [105].

In this thesis, we focus on the OPS networks (i.e., the final step of the current networking evolution), although the same concepts developed here can be easily modified to be effectively applied to OBS networks. This adaptation is an open issue and will be part of future works.

1.2 Motivations and environments

The technology limitation of the optical queuing motivates significant research efforts in recent years dealing with the design of simple scheduling policies able to provide QoS differentiation. The impossibility of pre-emptying packets already buffered makes unfeasible the implementation of conventional fair queuing scheduling commonly used in present day routers. At the same time, QoS schemes must be kept very simple to be effective in OPS where each node must be able to schedule tens of Terabits per second.

Even though numerous works have been done in the past on optical networks,

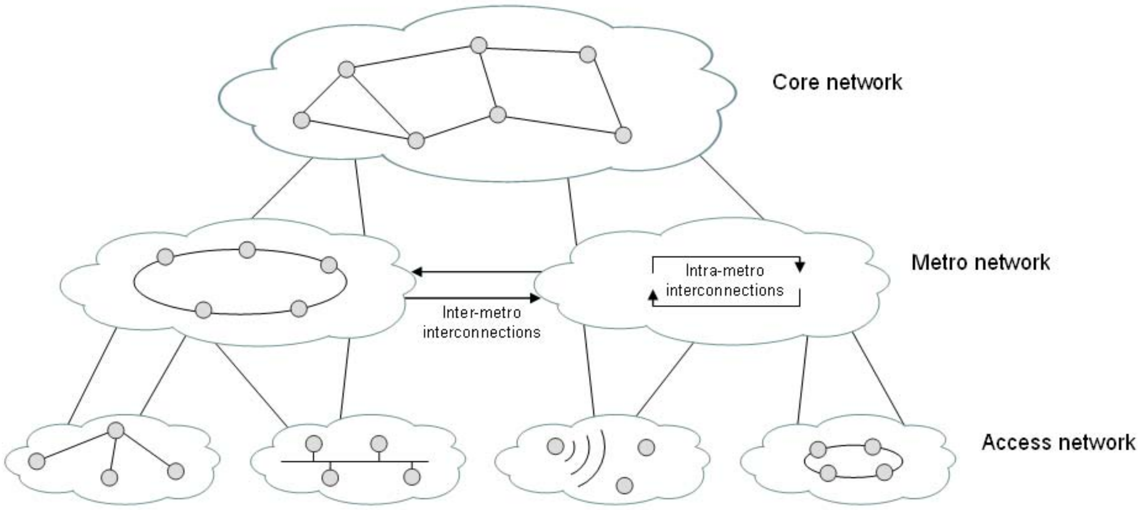

Figure 1.5: Network segments

few examples try to address the problem of a whole network performance analysis and design. At the same time, new emerging optical technologies are continuously opening up new opportunities for the development of novel network architectures and operative mechanisms. In this dissertation we hence deal with OPS networks placing particular attention to the QoS provisioning problem from an end-to-end perspective.

The hierarchy of communication networks can be viewed as consisting of three major segments (Figure 1.5): the access network, metro network, and wide area network[2]. The access network is responsible for collecting end-user traffic and is usually of less than tens of kilometers on its extension. Example of access networks include local/regional Internet Service Providers (ISPs), intra-building Ethernet, etc. The metro network is responsible for aggregating traffic from several access networks and routes it onto another metro (inter-metro traffic), onto the wide or directly delivers the traffic to its destination within the same metro (intra-metro traffic). The metro usually covers distances from tens of kilometers to few hundreds of kilometers. Finally, the wide area network (also known as core or backbone network[3]) interconnects metro networks and are typically more than hundreds of kilometers away.

In this thesis, we focus on both the metro and wide environment. From the networking point of view, the requirements and therefore the design guidelines of the former are generally different than the latter. We therefore carry out separated studies on metropolitan and wide area networks which are briefly described in the following subsections.

[2]Metro and wide are usually referred using the acronym MAN and WAN, respectively

[3]From now on, wide, backbone and core will be indiferently used to referring to this area network

1.2.1 Metro area networks

In the metro environment, the networks are generally *buffer-less*, in the sense that once information enters the network, it remains in the optical domain and does not face any buffers until it is delivered to its destination. Different network architectures can be envisaged from this simple concept (see Chapter 2 for a brief survey). In order to avoid collision on the individual WDM channels, Medium Access Control (MAC) protocols are needed which may integrate the support of QoS provisioning.

In this part of the thesis, we focus on two network architectures proposed in the DAVID project [40], namely multi-PON and multi-ring respectively. DAVID (Data And Voice Integration over DWDM) is a project funded by the Information Society Technologies program of the European Commission with the aim of providing advanced optical DWDM packet-switched network by developing innovative concepts and technologies [43]. The multi-PON and multi-ring architectures with their respective functional mechanisms (including the MAC protocols) have been proposed by other partners of the DAVID consortium.

Our task on this environment include: (i) the performance evaluation of these architectures, (ii) the identification of the drawbacks and of the open issues, (iii) the optimization of the proposed architectures and MAC protocols, and finally (iv) the proposal of QoS mechanisms to support multi-class traffic. The suggested solutions are also compared with new electrical solution targeting the same application environments (such as Resilient Packet Ring [96]) in a cost/performance perspective.

1.2.2 Wide area networks

In wide environment, queueing is achieved by Fibre Delay Lines (FDLs). As previously discussed, these buffers have many drawbacks: they are cumbersome, costly, and do not allow a new incoming packet to overcome other packets already queued, etc. Since the exploitation of the time is limited, frequency domain is deeply exploited to reduce the queueing requirements and, at the same time, to increase the network performance.

Recent works (for instance [16] [21]) suggest the integration of a connection-oriented path management protocol on top of the contention resolution algorithm which both improves the network performance and reduces the control complexity. In this context, protocols such as MPLS [91] can be extended to the OPS environment. These connection-oriented protocols are based on a distributed management scheme that provides and maintains Optical Virtual Connections (OVCs), called Label Switched Paths (LSPs) in the electrical MPLS context.

In this part of the thesis we focus on the connection-oriented OPS network scenario and we address two problems, namely the problem of setting up of the OVCs, properly configuring the forwarding table at the nodes, and the problem of providing QoS.

Concerning the former problem, at the OVC setup, each node must assign both the output port and the output wavelength to the OVC in such a way that the packets belonging to that OVC are always switched to the same output. This double setup problem is different with respect to the *classical* RWA problem in circuit-switched network because here the wavelengths are shared among several OVCs (in a packet-switched basis). In this study we do not deal with the problem of selecting the output port which depends on the routing protocol but we are interested in the election of the wavelength which may be set locally by each node using a *OVC-to-wavelength setup assignment* (OWSA) algorithm. In particular we show that intelligent OWSA procedures can considerably improve the performance of the switches. The intelligence relies on grouping the flows coming from the same input wavelength which allows to obtain the conflict-free situations and hence reduce the contention probability.

Concerning the latter problem, existing solutions to provide QoS in OPS networks are based on the following strategy: 1) design a contention resolution algorithm which minimizes the Packet Loss Rate (PLR), 2) apply a QoS mechanism (some form of resources reservation on top of the contention resolution algorithm) able to differentiate the PLR among two or more classes. Given that we are dealing with a connection-oriented model, here we suggest a new method based on the well known ATM scheme of defining different service categories which consists of defining different OPS service categories, each one based on a different contention resolution algorithm specifically designed to cope with the requirements of that category. With this technique, besides the PLR, also the packet delay and the computational complexity can be considered as QoS metrics.

1.3 Methodology and thesis outline

In order to attain the objective of the thesis, we use the following methodology for both metropolitan and wide area network environments:

1. Collect, analyse and identify the drawbacks of the previous works found in the literature on the same subject;

2. Propose novel or optimised solutions to overcome the drawbacks found in the previous step;

3. Set up ad hoc network simulators and simulation scenarios, thus carry out proper simulation evaluations for evaluating the merits of the proposals.

4. If the results are not as good as expected, repeat step 2.

The outline of the thesis is as follows.

In Chapter 1 we give a brief introduction of the network trend toward the optical switching paradigm and describe the main scopes and purposes of the thesis.

In Chapter 2, we presents an overview of the current state-of-the-art in the OPS paradigm. The application of the OPS concepts to both metropolitan and wide area network environments is also addressed.

Chapter 3 introduces the two OPS-based metro area architectures studied in this thesis, namely the multi-PON and multi-ring networks. We also identify the required services in such environments.

In Chapter 4 we discuss the state-of-the-art of the multi-PON architecture and describe our contributions on this subject.

In Chapter 5 we discuss the state-of-the-art of the multi-ring architecture and describe our contributions on this subject.

In Chapter 6 we compare the multi-ring and multi-PON solutions in a benchmarking study. We do not restrict ourselves to detailing the multi-PON and multi-ring performance, but also compare them to non-OPS technologies such as SDH, Ethernet and RPR.

In Chapter 7 we briefly introduce the OPS backbone environment focussing on the description of the connection-oriented environment.

In Chapter 8 we deal with the problem of setting up the optical virtual connections, properly configuring the forwarding table at the nodes. In this context, we study setup procedures to improve the switch performance compared to simple random schemes.

In Chapter 9 we address the QoS provisioning problem proposing a method based on the well known ATM scheme of defining different service categories. In particular, we define three different OPS service categories based on three different contention resolution algorithms

Chapter 10 draws the conclusions and indicates the future works.